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XXXIV. *Some Experiments on Tinfoil Contact with Dielectrics.*

By G. E. BAIRSTO, *M.Sc.*, *B.Eng.*

RECEIVED MAY 7, 1913. READ JUNE 13, 1913.

ALTHOUGH the questions connected with the effect of contact between the conductor and dielectric in the case of condensers have already been to some extent considered, a sufficient number of unsettled points remain which invited further consideration. In the course of a larger investigation on the properties of dielectrics the author was led to direct his attention to these questions, which were touched upon by Dr. J. A. Fleming and Mr. G. B. Dyke* in a recent Paper, and have also been discussed by Mr. Rollo Appleyard.†

The points examined by the author are as follows :—

1. The different effects of pressure and voltage upon tinfoil contact with celluloid as dielectric.

2. The effect of contact upon measurements made with alternating currents.

3. The effect of imperfect contact upon the accumulation of residual charge.

1. *The Different Effects of Pressure and Voltage upon Tinfoil Contact with Celluloid as Dielectric.*

In experimenting with dielectrics it is generally known that if we have tinfoil electrodes pressing against a sheet of dielectrics, and a heavy pressure applied to bring them into more intimate contact, the current a minute or two after the application of the voltage is slightly greater than the current at the time of switching on.

Mr. R. Appleyard has described some experiments on presspahn in which he compares the second minute deflection with the first minute deflection. He finds that for small loads the former is in general greater than the latter, but as the load increases a point is reached at which these deflections become approximately equal. For loads greater than this the second minute deflection was less than that of the first minute. He

* J. A. Fleming, F.R.S., and G. B. Dyke, B.Sc., "On the Power Factor and Conductivity of Dielectrics when tested with Alternating Electric Currents of Telephonic Frequency at Various Temperatures," "Proc." Inst. Eng., Vol. XLIX., p. 351.

† R. Appleyard "On Contact with Dielectrics," "Proc." Phys. Soc., 1905, Vol. XIX., p. 724-737; "Phil. Mag." Vol. X., p. 485; and "Science Abstracts," Vol. VIII.A, No. 2099, 1905.

also found that the apparent resistance gradually decreased with the pressure, and attained a fairly constant value at about 543 grams per square centimetre. He also found that increasing the voltage decreased the apparent resistance.

The following experiments, which go into the matter in more detail, were made with the object of trying to elucidate the cause of this increase of current after the first switching on of the current, by studying the effect at very low pressures as well as at the point at which perfect contact is obtained, and by allowing sufficient time (in most cases hours) for the current to reach its final steady value. In none of Mr. Appleyard's experiments does the increase of current amount to more than about 6 per cent., whereas by choosing a suitable dielectric, the author has been able to obtain increases of more than 40 per cent. The reason for this lies in the fact that with presspahn, the material used by Mr. Appleyard, the decrease in

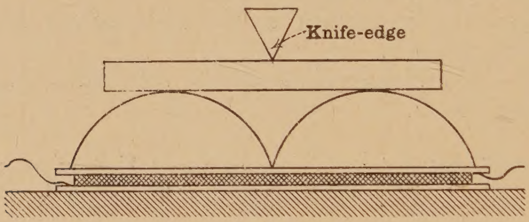


Fig. 1.

current due to absorption is of a greater order of magnitude than the conduction current, whereas celluloid, the dielectric which was used for the following experiments, has a much greater conduction current than displacement current, and so the effect of absorption has nothing like the influence it has with presspahn. Celluloid is therefore a much more convenient dielectric for use in investigating the effects under notice.

A single sheet of celluloid having an area of about 300 sq. cm. and thickness of 0·0762 cm., was placed between two well-smoothed tinfoil electrodes having an area of 205 sq. cm. each. It was placed in a testing machine with a thick piece of mill-board underneath and one above it, and the whole insulated with several layers of well-dried manilla paper. Two half-round steel pieces (*see* Fig. 1) with planed undersides served to distribute the pressure applied by the knife-edge of the testing machine to another flat piece of iron placed on top of both, the knife-edge being, of course, in a symmetrical position.

The E.M.F. used was 100 volts, and the current was measured by the direct deflection method.

The temperature during the whole course of experiments remained between the limits of 15·7° and 16·3°C.

Table I. gives a set of results for very low, and for moderate

TABLE I.

Weight in lbs.	Time.	10^{-8} amperes per sq. cm.	Weight in lbs.	Time.	10^{-8} amperes per sq. cm.
Approx. 5	...	1·16	250	½ min.	10·82
15	½ min.	2·38		1 „	10·85
	1½ „	2·43		2 „	11·04
	2 „	2·46		5 „	11·24
	5 „	2·47		10 „	11·26
25	½ „	3·19		15 „	11·3
	1 „	3·21		20 „	11·31
	5 „	3·22	300	½ „	11·38
35	½ „	3·63		1 „	11·41
	5 „	3·64		2 „	11·58
45	½ „	4·07		5 „	11·59
	1 „	4·12		15 „	11·77
	2 „	4·15		30 „	12·04
	5 „	4·16		45 „	12·47
50	½ „	4·39		1 hour	12·70
	2 „	4·48		1¼ „	12·81
	5 „	4·50		1½ „	12·92
60	½ „	4·70		2 „	13·28
	5 „	4·82	400	½ min.	13·97
	10 „	4·84		5 „	14·22
	20 „	4·87		15 „	14·62
70	½ „	5·24		½ hour	15·37
	2 „	5·27		1 „	16·38
	5 „	5·35		1¼ „	16·92
	10 „	5·36		2 „	17·70
80	½ „	5·56	500	½ min.	18·75
	2 „	5·59		1 „	18·91
	10 „	5·67		5 „	19·14
150	10 „	8·1		15 „	19·5
200	10 „	9·82		30 „	19·87
225	½ „	10·18		1½ „	20·8
	1 „	10·22		2 „	21·4
	5 „	10·48		3 „	22·15
	10 „	10·53		3¾ „	22·4
	15 „	10·53		24 „	22·3

pressures, each test being given sufficient time to allow the current to come to an absolutely steady value, after the first instantaneous increase had taken place. It will be seen that at low pressures the time required is short, *i.e.*, of the order of 5 to 15 minutes, but that as the pressure is gradually increased the time now required to reach a steady maximum is of the order, not of minutes, but of hours. Moreover, the increase

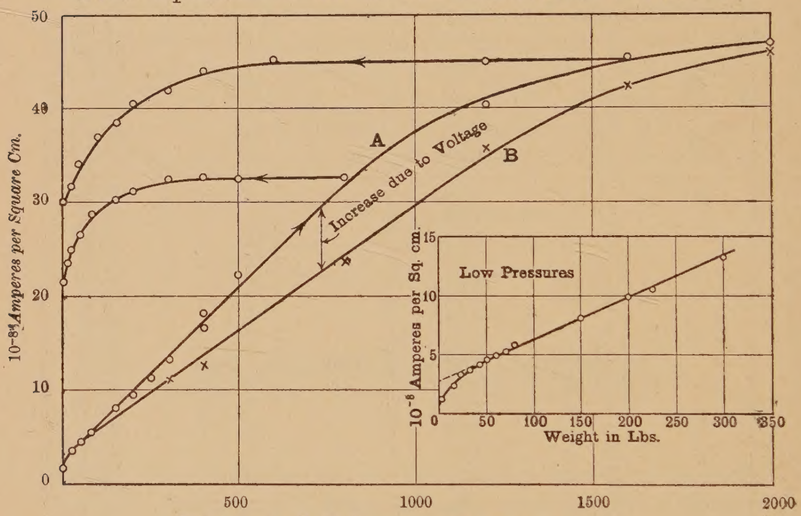
in current, at first small, becomes larger and larger as the pressure rises.

If we plot the current to pressure, as has been done in the inset to Fig. 2, we find that from 25 lb. upwards it follows a linear law :—

$$\text{Current} = a + b \text{ (pressure)}.$$

The short curved portion at the beginning of the straight line would seem to indicate that about 25 lb. was required to bring the tinfoil into a settled down condition on to the dielectric.

When a pressure of 300 lb. had been reached a break was



Weight in Lbs. (1,000 *lbs. corresponds to* 1·2 *atmospheres*).

FIG. 2.—VARIATION OF CURRENT WITH PRESSURE.

made in the experiments. The pressure was still kept on, but the voltage switched off and then re-applied after the lapse of 24 hours. Table II. gives the results of this test. It will be seen

TABLE II.—*Repeat Test.*

Weight in lbs.	Time.	10^{-8} amperes per sq. cm.
300	½ min.	11·26
	2 ,,	11·49
	5 ,,	11·58
	20 ,,	11·97
	30 ,,	12·22
	45 ,,	12·72
	1 hour	12·92
	1¼ ,,	13·14
	1½ ,,	13·48

that the current starts at practically the same value it initially had when the pressure of 300 lb. was first applied, and also gradually increases up to its previous maximum value. Moreover, the time required is practically the same in both cases, viz., about two hours. The current does not, of course, commence at exactly the same value, but at a point slightly lower, because in Table I. the dielectric had already reached a steady condition under voltage at a lower pressure, before the 300 lb. pressure was applied.

The above tests clearly show that voltage has quite as much effect as pressure in bringing about an intimate contact with tinfoil electrodes, and would also seem to indicate that each acts independently of the other.

TABLE III.

Weight in lbs.	Time.	10^{-8} amperes per sq. cm.	Weight in lbs.	Time.	10^{-8} amperes per sq. cm.
400	½ min.	12·63	1,200	1 min.	35·6
	5 ,,	13·20		5 ,,	35·8
	15 ,,	13·65		10 ,,	36·0
	30 ,,	14·20		15 ,,	36·2
	1 hour	14·49		30 ,,	36·6
	1½ ,,	15·5		1 hour	38·1
	2 ,,	16·1		3 ,,	40·1
	2½ ,,	16·2		5 ,,	40·4
	3½ ,,	16·7	1,600	½ min.	42·3
800	½ min.	22·15		1 ,,	42·4
	1 ,,	22·35		5 ,,	42·7
	10 ,,	23·1		15 ,,	42·8
	20 ,,	23·6		30 ,,	43·4
	30 ,,	23·95		1 hour	44·5
	45 ,,	24·6		1½ ,,	45·1
	1 hour	25·25		2½ ,,	45·3
	1¼ ,,	25·8		3½ ,,	45·4
	2¼ ,,	28·1		24 ,,	45·45
	2½ ,,	28·75	2,000	½ min.	45·8
	3 ,,	29·85		10 ,,	46·0
	4 ,,	31·9		30 ,,	46·4
	4½ ,,	32·1		1 hour	46·8
	5 ,,	32·6		1½ ,,	46·9
				2½ ,,	46·9

To test this still further, both the pressure and voltage were removed, and the whole system left to itself for a day, and another set of experiments, embodied in Table III., made, in which the pressure was applied in a series of equal increments of 400 lb., starting at 400 lb., and going up to 2,000 lb.

Fig. 3 shows how the current increases with the time for these different increments of pressure. In continuation of the

low pressure series, it will be seen that the time required for the current to reach its final value is longer and longer, reaches a maximum value of five hours at 800 lb., and afterwards decreases as the pressure rises to the point at which intimate contact is made with the dielectric.

In Fig. 2, curve A, the final values of the current are plotted against pressure; at 2,000 lb., the curve has practically become flat.

At the end of the 800 lb. test the system was again left to itself for 24 hours without pressure or voltage being on, and a repeat test made at 800 lb. The results are denoted by crosses on Fig. 3. As with the 300 lb. repeat test, they lie on

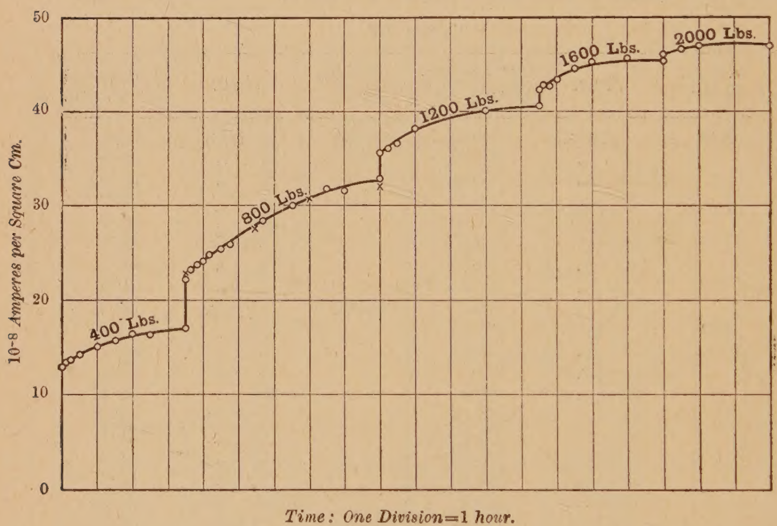


Fig. 3.

the same curve, and moreover the current, after the instantaneous increase, is practically the same as in the first case, showing that the pressure increments are so large that we may assume that for any one of the five pressures the current at the end of the instantaneous increase is the same as if the pressure had been applied immediately without any intermediate step.

Using this information, it is instructive to tabulate what may be called the instantaneous, and the secondary increments in current, and their percentages of the total increments. This

has been done in Table IV. Fig. 4 shows how the ratio of instantaneous increase to total increase and of secondary increase to total increase vary with the successive pressure

TABLE IV.

Weight in lbs.	Current in 10^{-8} amperes/sq. cm.			Increase of current.			Instantaneous increase.	Secondary increase.
	Initial.	After the instantaneous increase.	Final.	Instantaneous.	Secondary.	Total	Total increase.	Total increase.
400	2·73	12·63	16·7	9·90	4·07	13·97	0·71	0·29
800	16·7	23·65	32·2	6·95	8·55	15·5	0·45	0·55
1,200	32·2	35·6	40·4	3·4	4·8	8·2	0·41	0·59
1,600	40·4	42·3	45·45	1·9	3·15	5·05	0·38	0·62
2,000	45·45	45·80	46·90	0·35	1·10	1·45	0·24	0·76

increment. The secondary increase, at first a small percentage of the total increase, becomes larger and larger, until at high pressures it accounts for practically all of the increase.

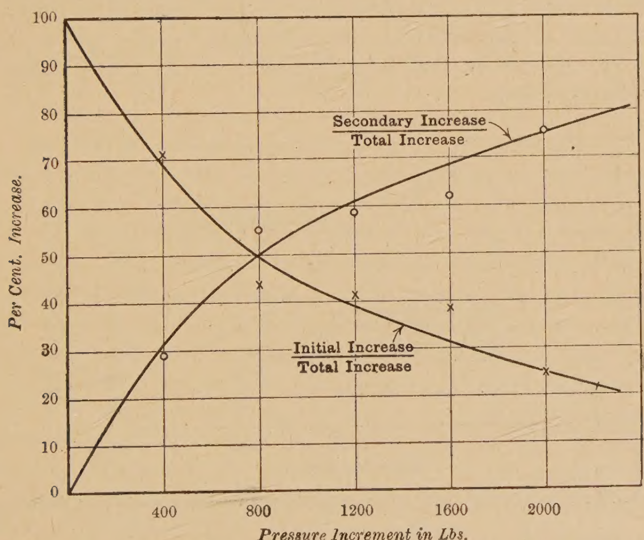


FIG. 4.—SHOWING THE PERCENTAGE INCREASES OF CURRENT FOR SUCCESSIVE PRESSURE INCREMENTS.

Considering now the secondary increase as a function of the pressure on the tinfoil, Fig. 5 shows how these two quantities are connected. At low pressures exceedingly small, the secon-

dary increase becomes larger and larger as the pressure increases, attains a maximum value at about 800 lb., and gradually falls to a small value again. In Table V., column 2 corresponds to that of column 3 of Table IV., and in column 4 are given the values of the ratio of the secondary increase to the current after the instantaneous increase took place, or, in other words, the ratio of the difference between the final and

TABLE V.

Weight in lbs.	Current in 10^{-8} amperes per sq. cm. Before secondary increase (1).	Current in 10^{-8} amperes per sq. cm. After secondary increase (2).	Per cent. increase $\frac{(2)-(1)}{(1)} \cdot 100.$
300	11·26	13·48	20·0
400	12·63	16·70	32·0
800	23·65	32·20	36·0
1,200	35·60	40·4	13·5
1,600	42·30	45·45	7·5
2,000	45·80	46·90	2·5

initial deflections of the galvanometer to the initial deflection. The variation of this quantity with pressure is also given in Fig. 5. It will be seen that at about 650 lb. it attains a value of over 40 per cent.

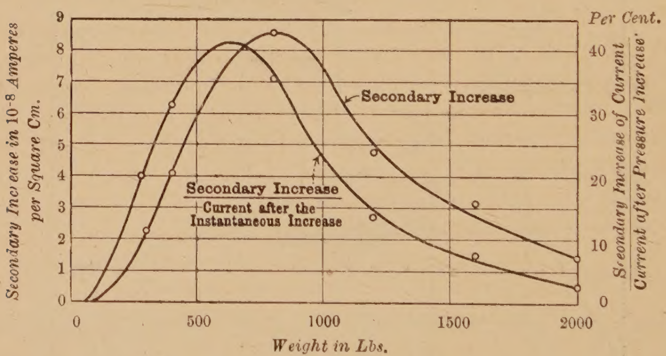


FIG. 5.—VARIATION OF SECONDARY INCREASE OF CURRENT WITH PRESSURE.

It is evident from the above results that the secondary increase is due wholly and solely to the application of the voltage, and we may construct as in Fig. 2 a curve B, such that for any pressure its ordinate is equal to the current at the first minute of application of the voltage, and the difference between it and curve A gives the secondary increase due to the voltage.

An ordinate of curve B measures the degree of intimacy of contact due to the pressure, and the difference between A and B the further increase due to the action of the voltage.

At two stages in the last-mentioned series of experiments, viz., at 800 lb. and 1,600 lb. respectively, the pressure was gradually reduced down to zero again. The current-pressure curves are given in the two upper curves of Fig. 2. It is to be noted in each case that the current does not begin to fall away until the pressure has been reduced to about one-third of its value, and that also in both cases the current when the pressure has been reduced to zero, was about 65 per cent. of its value at full pressure.

For convenience the forces applied to the tinfoil have been expressed in pounds weight applied by the knife-edge of the testing machine. Since the area over which the pressure was distributed amounted to 290 sq. cm., 1 lb. corresponds to a pressure of 1·26 grams per square centimetre, so the pressure exerted by 2,000 lb. on the tinfoil is equal to 2,500 grams per square centimetre, or since 1 kilogram per square centimetre is equal to 0·97 atmosphere, this corresponds to a pressure of 2·4 atmospheres. This is the pressure that was required to bring the tinfoil into an intimate contact with the celluloid.

The effects described above may be explained as follows :—

Let (*a*) Fig. 6 represent a section, very much magnified, taken through the dielectric and its tinfoil electrodes. It represents a number of hollows with corresponding humps full of air, current being able to pass through the bases of the hollows. The effect of pressure will be twofold. Firstly, to make one hump into two, say, as in Fig. (*b*), or secondly to flatten it as in (*c*). In the first case we should have an instantaneous increase of current, as soon as the pressure is applied. In the second case, there will be little increase of area of electrode in contact with the dielectric, and therefore very little instantaneous increase of current. If, however, we consider the distribution of the stream lines of current we shall have a system as shown in the figure, such that at a point A, not far from the base of the hump, there will be a P.D. between that point of the dielectric, and B. a point on the dielectric vertically above it. This P.D. acting across the very thin film of air will give rise to a large potential gradient, and therefore a large local mechanical force. This force gradually pulls more and more of the surface of the tinfoil down on to the dielectric, at first quickly, because the angle A P B is acute, and then

slowly, for A.P.B. becomes as in Fig. (*d*), obtuse. The current therefore increases quickly at first, and then reaches its maximum value more slowly, which is just what we have seen by experiment (Fig. 3) actually happens.

The contact is therefore made up of these two parts, the primary increase, and the secondary increase due to the action of the voltage. The extent to which each is important will depend on the magnitude of the applied pressure. Now it will

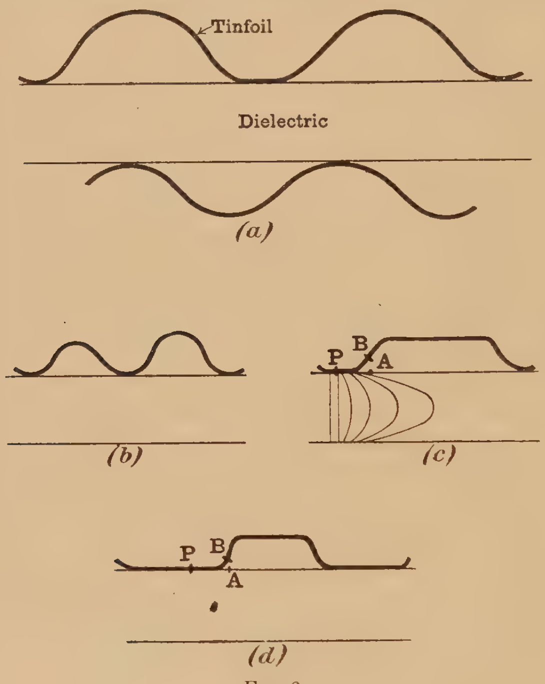


Fig. 6.

be obvious from geometrical considerations that the angle at the base of hump in (*b*) will be smaller than in (*a*). So at low pressures the secondary increase will be small, and will increase as the pressure increases, and the hump becomes smaller. In a series of tests, therefore, made with successive equal increments of pressure, the ratio of the secondary increase of current to the total increase of current should increase with the pressure increment. This agrees with the results depicted in Fig. 4.

Again, considering the absolute value of the secondary

increase, and its variation with applied pressure, we have seen that it is small at small pressures, and increases as the pressure rises. On the other hand, when the pressure is sufficiently large enough to bring the tinfoil into perfect contact with the dielectric, there can be no secondary increase, because all the tinfoil is now in contact. This we have seen in the above is what takes place (*see* Fig. 5). Between these two pints of low and of high pressures there is a maximum which will depend upon a number of factors, the principal of which will probably be the nature, size and shape of the humps, and the mechanical properties and thickness of the tinfoil. Absorption will also, of course, play a part in reducing the value of the secondary increase as the pressure rises.

We have seen that a repeat test made at the same pressure after the voltage has been removed for some time, leads to practically the same current-time curve. This is to be explained by the natural resilience of the tinfoil causing it to spring back again. This effect would only be wiped out by applying a very large pressure, and then a repeat test made at the original pressure would lead to quite different results.

Since the secondary increase is due to the presence of the voltage, it follows that when the system has become steady at a given pressure below that at which intimate contact takes place, and we now decrease the voltage we should expect to find an increase in the apparent resistance. This is illustrated by Table VI., and agrees with Mr. Appleyard's observations previously mentioned.

TABLE VI.—*Variation of Apparent Specific-resistance of the Dielectric with Voltage after the Pressure had been brought up to* 1,600 *lb.*

Volts.	10^{-8} amperes per sq. cm.	Ohms per cu. cm.
97	45·5	$0{\cdot}0283 \times 10^{12}$
74	34·2	0·0287 ,,
49	21·5	0·0298 ,,
24	9·98	0·0316 ,,

2. *The Effect of Contact upon Measurements made with Alternating Currents.*

We have seen that in direct-current measurements considerable errors are liable to be made in deducing the specific resistance from the current flowing through the dielectric when the contact is a tinfoil one, but when we are dealing with the losses in dielectrics for alternate currents of high frequency it

would appear that the error due to bad contact is very much diminished. Dr. J. A. Fleming and Mr. Dyke* have shown theoretically that it should be very much diminished in these circumstances. They show that by considering the condenser with its tinfoil armatures as equivalent to a thin air condenser in series with a high resistance R equal to the resistance *per se* of the condenser, and deducing an expression for the effective conductance of the combination for alternating currents of a given frequency, the presence of the thin air film has very little influence on the observed, or apparent conductance of the system for alternating currents of that frequency.

We shall here consider a more general case, and suppose the system equivalent to a condenser of dielectric having capacity

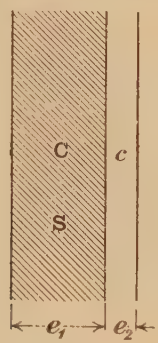


FIG. 7.

C, and conductance S, in series with a thin air condenser c (Fig. 7).

Let i=current flowing through the dielectric, e_1 and e_2 =E.M.F.s across C and c respectively, and E sin pt = the applied E.M.F.

Then
$$i = \mathrm{C}\frac{de_1}{dt} + \mathrm{S}e_1$$
$$= c\frac{de_2}{dt};$$
$$\therefore \quad i(\mathrm{C}+c) = \mathrm{C}c\frac{de}{dt} + \mathrm{S}ce_1$$
$$(\mathrm{C}+c)\frac{di}{dt} = \mathrm{C}c\frac{d_2e}{dt^2} + \mathrm{S}c\frac{de}{dt} + \mathrm{S}c\frac{de_2}{dt},$$

* "Journal" of the Institution of Electrical Engineers, 1912, Vol. XLIX., p. 351.

or
$$(C+c)\frac{di}{dt}+Si=-CcEp^2\sin pt+Sc\cos ptEp$$
$$=-Ecp\sqrt{C^2p^2+S^2}\sin(pt-\phi),$$
where
$$\tan\phi=\frac{S}{Cp},$$
$$\therefore\quad i=\frac{Ecp\sqrt{C^2p^2+S^2}}{\sqrt{S^2+(C+c)^2p^2}}\sin(pt-\phi-\theta), \quad (1)$$
where
$$\tan\theta=\frac{(C+c)p}{S}.$$

The power therefore wasted in the system is—
$$W=-E^2cp\sqrt{\frac{S^2+C^2p^2}{S^2+(C+c)^2p^2}}\cdot\frac{\cos(\phi+\theta)}{2}$$
$$=\frac{c^2p^2}{S^2+(C+c)^2p^2}\cdot\frac{SE^2}{2}. \quad \text{. . . . .} \quad (2)$$

The equivalent conductance is therefore
$$=\frac{c^2p^2}{S^2+(C+c)^2p^2}S. \quad \text{. . . . .} \quad (3)$$

Also we have the total admittance from (1)—
$$Y=\frac{cp\sqrt{C^2p^2+S^2}}{\sqrt{S^2+(C+c)^2p^2}},$$
and since $Y^2=$ (equivalent conductance)$^2+$(apparent capacity)^2 p^2, we get on reduction the following expression for the apparent capacity—
$$\frac{c[S^2+Cp(C+c)p]}{S^2+(C+c)^2p^2}.$$

Since the value of S/Cp for most dielectrics at ordinary temperature is of the order of 0·01, or less, and S/cp will therefore be still smaller, we deduce the following approximate expressions :
$$\left.\begin{aligned}\text{Equivalent conductance } &=\left(\frac{c}{C+c}\right)^2 S\\ \text{Equivalent capacity } &=\left(\frac{c}{C+c}\right)C\\ \text{Apparent power factor } &=\left(\frac{c}{C+c}\right)\frac{S}{Cp}\end{aligned}\right\} \quad \text{. . .} \quad (4)$$

In Table VII. are given the results of two tests made in order to see what is the actual difference that can be obtained with a tinfoil contact of this kind. They refer to a certain condenser made up of celluloid in very thin sheets 0·0146 cm. in thickness.

TABLE VII.
(1 Bimho $=10^{-12}$ mho.)

Test.	1. Pressure on.			2. Pressure off.		
Frequency.	Capacity C_P in micro-micro-farads.	$\frac{S_P}{C_P p}$.	Conductivity σ_P in Bimhos per cm. cu.	Capacity C_0 in micro-micro-farads.	$\frac{S_0}{C_0 p}$.	Conductivity σ^0 in Bimhos per cm. cu.
920	1,780	0·0228	59·9	1,670	0·0211	52
2,760	1,755	0·0192	149·0	1,665	0·0182	134
4,600	1,730	0·0183	233·0	1,630	0·0174	211

In test No. 1 the condenser was squeezed together with such a pressure as by the previous experiments, would give an

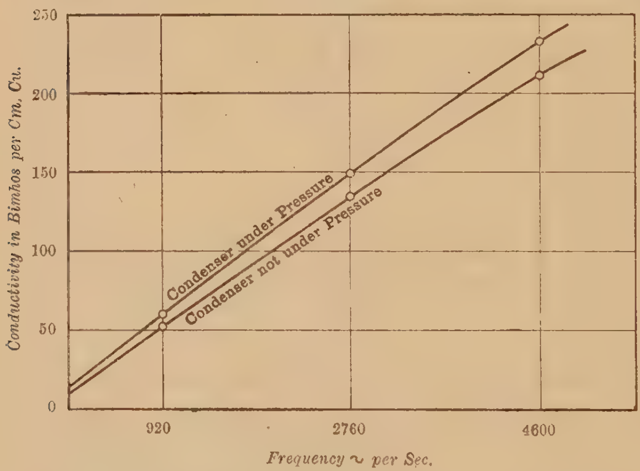


FIG. 8.—SHOWING THE EFFECT OF CONTACT UPON MEASUREMENTS MADE WITH ALTERNATE CURRENTS IN CELLULOID CONDENSER.

approximately intimate contact, whereas in test No. 2 it was under no pressure, but was lightly bound round with tape so as to just hold it together. The measurements were made with the Fleming and Dyke variable capacity bridge. The

results are also depicted in Fig. 8, and expressed as percentages in Table VIII. The suffixes P and 0, refer to pressure on, and pressure off, respectively.

TABLE VIII.

Frequency.	Per cent. variation of		
	$\frac{C_P}{C_0}$.	$\frac{S_P}{C_P p} \Big/ \frac{S_0}{C_0 p}$.	$\frac{\sigma_P}{\sigma_0}$.
920	6·5	6·0	15·0
2,760	5·5	5·5	10·5
4,600	5·0	5·0	10·0

Now, the influence of the bad contact is two-fold ; firstly, it decreases the apparent capacity by inserting in series with the condenser under test a very large, but still finite, air condenser. This by the above equations causes a decrease in the apparent conductance. Secondly, it decreases the magnitude of that component of the conductivity which is independent of the frequency, *i.e.*, the purely ohmic conductivity, because of the decrease in the area of contact.

The equations (4) give us a means of separating the two effects, for according to them the percentage change in the equivalent conductance is twice that of the equivalent capacity. Now the average percentage change of C is about 5·5, and this is just about half the change in the conductivity at 2,760 and 4,600 ∿. At 920 ∿, however, there is a difference at about 5 per cent. This is the amount of error due to the second effect, *i.e.*, bad contact, decreasing the ohmic part of the conductivity. At lower frequencies still this would be still larger. Hence we can say that for telephonic frequencies the main influence of a bad contact is to lower the observed conductivity by inserting a capacity in series with the condenser under test.

It must be understood that the above case is a very extreme one, since the dielectric was very thin, and the contact made very much worse than would occur in practice. A further test, in which the tinfoil after being carefully smoothed and rolled on to the celluloid, and the whole tightly bound with tape between glass plates, and then wedges inserted between the tape and the glass, gave a maximum change of C of 2·5 per cent. and a change in σ of 4·5 per cent. when tested in this condition and then under pressure. For dielectrics of greater thickness the change would be less.

3. *The Effect of Imperfect Contact upon the Accumulation of Residual Charge.*

In a well-known lecture experiment, to show the existence of residual charges in dielectrics, a Leyden jar is charged to a high voltage for a short time, and then by means of a pair of discharging tongs is discharged again. On being left to itself for a time and properly insulated, a further discharge almost as strong, as indicated by the spark, may easily be obtained.

In view of the previously described experiments, the question presents itself as to whether this second discharge is entirely due to the presence of a residual charge in the glass, or whether we are not really dealing with a case of very bad contact between the tinfoil armatures of the jar and the glass dielectric.

TABLE IX.

Time.	Voltage of residual charge.				
	Both electrodes tinfoil. (1)	Both electrodes tinfoil. Better contact. (2)	One electrode tinfoil. Second electrode mercury. (3)	Both electrodes uncleaned mercury. (4)	Both electrodes clean mercury. (5)
5 secs	50·5	41·5	29·0	22·0	18·0
10 ,,	53·0	...	36·0	28·5	21·0
15 ,,	...	44·5	...	...	22·0
20 ,,	53·5	...	40·0	31·5	...
30 ,,	49·0	47·0	42·0	32·5	22·0
1 min.	41·0	43·5	41·5	33·0	18·0
$1\frac{1}{2}$,,	33·5	39·5	39·5	31·0	15·5
2 ,,	27·5	34·5	38·0	29·0	13·5
3 ,,	22·0	27·5	36·0	25·5	9·5
4 ,,	18·0	23·0	32·0	22·0	7·0
5 ,,	14·0	19·0	29·0	19·0	4·5
6 ,,	...	15·5	...	16·0	...
$7\frac{1}{2}$,,	7·0	12·0	21·0	13·5	2·5
10 ,,	4·0	8·0	16·0	10·5	...

Table IX gives the results of some experiments made to decide this point. A glass tube about 1 in. in diameter and 4 in. long was used as the condenser. It was carefully insulated on a paraffin block, and could either be covered with tinfoil or else filled with mercury and placed inside another and larger tube full of mercury so as to obtain two electrodes in intimate contact with the glass. This tube was connected up as shown (Fig. 9) with a two-way mercury switch made out of a paraffin block, arranged so as to charge the glass condenser with a small

insulated battery of secondary cells of about 100 volts for a given time, and then on throwing over the switch, to momentarily short-circuit it, and finally by removing the cross-connecting wires to leave the tube connected with an electrostatic voltmeter which indicated the growth of the residual charge. The voltmeter was one of Ayrton and Mather's, and had a very short period. It gave about 26 cm. deflection at 2 metres for 100 volts. Its insulation as well as that of the whole circuit was considerably better than that of the glass tube itself.

In the first column of Table IX are given the values of the P.D. between the tinfoil armatures at different times after a momentary short circuit, the tube having been previously charged for 10 minutes at a voltage of 99. The results have been plotted in curve 1 of Fig. 10. The residual charge grows very rapidly, and in about a quarter of a minute has reached its maximum potential. This maximum potential of the re-

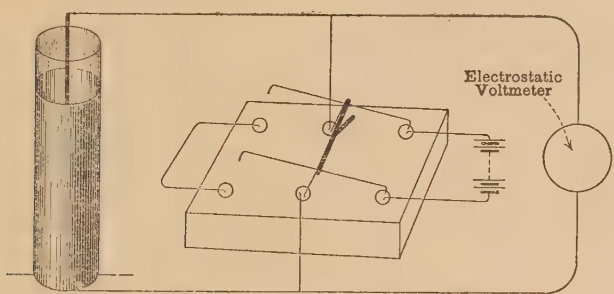


FIG. 9.

covered charge is more than half that of the original potential. It then dies away as the charge leaks through the dielectric. In this case the tinfoil both inside and out were simply pressed into contact with the glass tube. In the case of test No. 2 the contact was made a better one by binding the tinfoil with fine wire on the outside, and thoroughly pressing down the inside armature, and here we see that the residual charge does not attain quite as high a value, only 47 volts. In the next test, No. 3, the outside tinfoil was left in position, but the inside coating removed and replaced with clean mercury. The maximum potential of the charge recovered is still lower—42 volts.

In case No. 4 both electrodes were formed of mercury that had been standing about the laboratory for some months, and

was very dirty and dusty. In this case we have a still further drop of maximum voltage to 33.

Finally, in the fifth test, both electrodes were made of mercury that had been thoroughly cleaned, and we see that the maximum voltage of the recovered charge, in this case the true residual charge, is now only 22 volts, *i.e.*, is just half what it was with tinfoil armatures.

The source of these differences, as we have said, lies in the degree of contact produced between the armatures and the dielectric. If part of the tinfoil is not in contact with the glass,

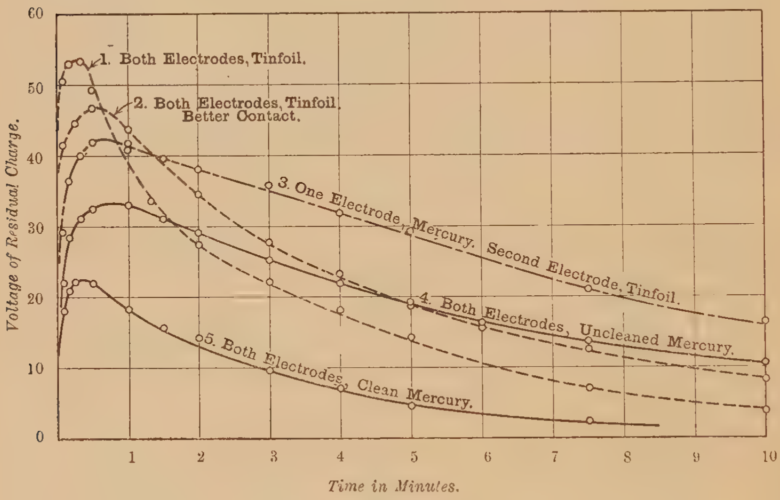


FIG. 10.—SHOWING THE EFFECT OF CONTACT ON THE ACCUMULATION OF RESIDUAL CHARGE.

Dielectric: Glass tube charging volts, 99. Time of charge, 10 minutes. Momentary Short Circuit.

the portion of the condenser corresponding to it is not discharged at the moment of short circuit, but the charge in it gradually comes out afterwards, and leaking along the surface of the glass, charges up the tinfoil and thus gives rise to an increased charge over and above the residual charge left in the dielectric.

There is one point in connection with Fig. 10 that requires further explanation. It will be noticed that as we proceed from curve 5 to curve 3, *i.e.*, as the contact becomes worse, the rate of fall of potential due to leakage through the glass

becomes smaller and smaller. This necessarily follows from the law—

$$\frac{dV}{dt} = -\frac{V}{CR},$$

where V is the potential at any time t, and C and R, the capacity, and insulation resistance of the condenser. C is approximately constant, and R will be inversely proportional to the area of contact,

$$\therefore \quad \frac{dV}{dt} \propto \text{V(area of contact)},$$

that is to say, the rate of fall of the logarithm of the potential is proportional to the area of contact. But when we make the contact still worse by employing a loose tinfoil contact, C will be very materially reduced, on account of the thin film of air in the humps of tinfoil. Moreover, the dielectric constant of this air condenser is only about one-eighth of that of the glass.

The net result of this will be an increase in the rate of fall of potential more than the decrease due to lack of contact, and hence the curves 1 and 2 eventually fall below those of 3, 4 and 5.

In conclusion, we may say that if we have a condenser with tinfoil armatures, as in the Franklin jar with its rigid metallic coatings, the recovery of a residual charge will be obscured by the presence of creeping surface charges coming out of the undischarged portions of the dielectric.

I take this opportunity of expressing my thanks to Dr. J. A. Fleming, F.R.S., for his advice and suggestions in this work, and to Prof. Cormack for placing the testing machine at my disposal. The experimental work has been carried out in the Research Laboratory of the Electrical Engineering Department of University College, London.

ABSTRACT.

This Paper describes some experiments showing how the accuracy of the different kinds of electrical measurements that are made on condensers is influenced by the use of an imperfect tinfoil contact.

1. In connection with the measurement of the direct-current conductivity of a condenser having tinfoil armatures, the experiments of Mr. Appleyard ("Proc. Phys. Soc.," 1905, Vol. XIX., p. 724), in which the current a minute or two after the first switching on of the current was greater than that at the time of switching on, are referred to. These experiments go into the matter in more detail. By choosing a suitable dielectric—celluloid, which has a

conduction current of a greater value than the rate of change of displacement current—it was found possible to greatly increase the magnitude of these secondary increases in current.

At very low pressures there is very little increase of current, and moreover what little increase there is is over in a few minutes, but as the pressure is increased the secondary increase gradually becomes larger and takes longer to attain its maximum value. The maximum effect was reached at about 750 grammes/sq. cm., when the increase of current amounted to 40 per cent., and the time required $5\frac{1}{2}$ hours. At very large pressures, when the contact becomes an intimate one, the increase of current becomes smaller again and the time required also smaller.

If the pressure is left on and the voltage removed for some hours a repeat test follows the same course, the current starting at the same value and attaining the same maximum value. Voltage has, therefore, quite as much effect as pressure in bringing about an intimate contact and acts independently of it.

By considering the geometry of the tinfoil humps, an explanation of these various effects is given, and the different ways in which the pressure and the voltage increase the degree of contact between the dielectric and the tinfoil armatures are described.

2. While considerable errors are liable to be made in deducing the specific direct current conductivity of a dielectric between tinfoil armatures, the same is not true for measurements of the alternating-current conductivity. The influence of the bad contact is twofold. Firstly, it decreases the apparent capacity by inserting in series with the condenser under test a very large but still finite air condenser. This causes a decrease in the measured conductance. Secondly, because of the decrease in area of contact, it decreases the magnitude of that component of the conductivity which is independent of the frequency—*i.e.*, the purely ohmic conductivity.

By considering the system as equivalent to a leaky condenser in series with a very large capacity due to the air film, expressions are deduced for the equivalent capacity, conductance and power factor, and these expressions furnish us with the means of separating out the two above effects.

It is shown experimentally, even under the worst possible circumstances, the dielectric being only lightly bound up with the interleaved tinfoil, that for telephonic frequencies the maximum difference between the observed conductivity and true conductivity is 15 per cent. and of capacity is 5 per cent. With the condenser tightly bound with tape and wedges of wood inserted, the maximum difference was only 4·5 per cent. in the conductivity and 2·5 per cent. in the capacity.

3. Finally, the influence of imperfect contact upon the accumulation of residual charge is considered. It is shown that if we have a condenser with tinfoil armatures, as, for instance, in the Franklin jar, with its rigid metallic coatings, the recovery of a residual charge is obscured by the presence of creeping surface charges coming out of the undischarged portions of the dielectric leading to an apparent residual charge much more than the true residual charge left in the dielectric.

DISCUSSION.

Dr. J. A. Fleming thought the Paper contained much valuable information. He emphasised the difficulty and importance of getting rid of the air film. For many dielectrics, such as glass or sulphur, a considerable pressure could not be applied. In this case the tinfoil could be squee-geed on to the dielectric when the condenser was made or the condenser could be put in a vacuum subsequently. For a constant condenser it was also necessary that there should be no chemical action between the metal plates and the dielectric such as occurred, for instance, in the case of copper foil and celluloid. He thought Mr. Bairsto's experiments on residual charges were very interesting. Theorists had attributed the whole effect to the properties of the dielectric and not to the bad contact between it and the electrodes. The Paper was also useful in pointing out the pitfalls of experimental work on the subject.

Mr. R. Appleyard: It is very gratifying to find that Mr. Bairsto has been able to confirm the results which I had the privilege of describing to the Physical Society in the Paper of June, 1905, which he has cited. Judging from some remarks of the author in his present communication, I think he must have overlooked a Paper on dielectrics, read before the Physical Society in May, 1894, in which I set forth the results of tests on celluloid sheets, similar to those now adopted by Mr. Bairsto. In that Paper the effect, upon dielectric resistance, of increasing the testing voltage is clearly shown for the case of hard metallic electrodes, and the effect of residual charge in celluloid sheets is also considered. Mr. Bairsto has attacked an intricate and fascinating group of phenomena in an ingenious and helpful manner, and he has given us a Paper of considerable value. I am glad that he has adhered to the direct-reading method of examining the changes in dielectric resistance. He probably has some good reason for maintaining the current on until the steady reading has been approached, but I would recommend him to examine the merits of taking the reading after a prescribed period—say, of one minute—after the first switching on of the current, and to work out the megohms from that reading as a standard result. Resistances corresponding to subsequent minutes can of course be worked out also if desired. The truth is that the steady state is reached only after infinite time; and, moreover, a number of noteworthy things are happening during the first minute. In the second part of his Paper Mr. Bairsto embarks upon an investigation of the phenomena of alternating currents which has no well-defined relation to the results observed by him in the first part of his research. The conductance to direct currents referred to in the first part must be distinguished from the conductance leakance to alternating currents investigated in the second part. Conductance leakance is simply a coefficient used in representing the watts lost in the dielectric with alternating currents, as shown in his equation (2). In the direct-current case, with tinfoil, he is measuring the dielectric resistance, plus the bad contact resistance in series with it. In the alternating-current case he is measuring a dielectric-hysteresis effect, which might conceivably be measured even though there were complete discontinuity between the dielectric and its electrodes; or, in other words, even though the surface-contact were of infinite resistance. Again, can the author be sure that the increase of capacity shown in Table VII. is not due to diminution of distance between the electrodes, resulting from the increase in mechanical pressure. I wish he would extend the research to obtain positive measurement of the increase of pressure mentioned on p. 309. The diminution of resistance with increase of voltage is not restricted to tinfoil. It is shown in my Paper of October, 1894, to be strongly marked in the case of hard brass plates. The result would, therefore, appear to be due rather to change of contact-resistance than to change of capacity, for the change of capacity in this case is minute. The author's experiments on residual change are of very great value, and they suggest a most useful line of research.

Mr. E. H. Rayner remarked that it was always assumed that pressure had no direct influence on the properties of the dielectric, but simply improved the contact between the electrode and the dielectric. Pressure might directly decrease the resistance of the dielectric in the same way as a wet sponge would have its resistance diminished by pressure.

Dr. A. Russell agreed with Mr. Rayner's remarks. Celluloid was far from being homogeneous. Mr. Appleyard, he remarked, had shown that the insulation resistance of a condenser is not constant, but a function of the applied voltage, decreasing as this is increased. Hence, Ohm's law cannot be applied. He pointed out that the author had represented his condenser as a capacity shunted by a resistance, all in series with another capacity (that of the air film). This would make the leakage current zero on the direct current test. The representation should be two condensers in series all shunted by the leakage resistance.

Mr. G. L. Addenbrooke remarked that he had tried in a rougher way some of the same experiments now described. He remarked that Mr. A. Campbell had suggested blackleading the surfaces of the dielectric to do away with the effect of the air film. He also emphasised the importance of heating in the dielectric due to energy losses. For celluloid which had a temperature coefficient of 10 per cent. per degree this was an important consideration.

Mr. W. Duddell remarked that the Paper showed the importance of a thin air film in the determination of the capacity and conductivity of a condenser. For standard condensers the maker knew that if the air was not excluded between the tinfoil and the dielectric the capacity would not remain constant. If a high voltage were applied to such a condenser and left on for some time, the capacity afterwards would be found to be permanently altered. Even with as low a voltage as 200 volts brush discharges could take place from the tinfoil into the air film. This brush discharge into the air film at 200 volts could be actually seen in a dark room if one electrode be replaced by water, while the other one was tinfoil and the dielectric was mica. This brush discharge was also an important consideration in the slots for the windings of dynamos and alternators.

Prof. C. H. Lees expressed his interest in the third section of the Paper on the residual discharge. He would like the author to see whether tinfoil electrodes under pressure gave the same residual discharge curve as the mercury electrodes.

Mr. W. Eccles: Mr. Bairsto's excellently planned experiments go far towards removing the obscurity surrounding the subject. The explanation of the effects of pressure and voltage on the contact between electrode and dielectric will probably be widely accepted; but it seems to me that this purely mechanical explanation, based on the distortion of air-filled blisters, is somewhat insufficient. The experiments show that within limits the recovery from applied pressure and voltage is so complete as to suggest the perfect elasticity of the combination, yet, somewhat in contradiction to this, there is a very slow development or decay of the secondary or electro-mechanical effect. The author's mechanical explanation does not appear to account for this viscous part of the phenomenon. I suggest that it may be largely accounted for by supposing that after a voltage is applied there occurs a creeping of charge over the dielectric surface from the tinfoil contact areas (just as described by the author in discussing residual charge), and, therefore, a gradual and not an instantaneous increase in the area of tinfoil attracted into contact. This supposition added to the author's mechanical explanation appears to be sufficient to explain the experiments.

The Author, in reply to Mr. Appleyard, said the first two sections of the Paper referred to two entirely different sets of measurements, and the main object of the second part was to show that the presence of a discontinuity between the dielectric and its electrodes had no very appreciable effect upon the measurement of the power absorbed by the condenser due to the *alternating current* conductivity, which was something quite different from the

conductivity for direct currents. The point had been raised as to whether the capacity changes in Table VII. were due to the mechanical pressure. It was found that the resistance of the celluloid, measured with the full pressure on, was practically the same as when measured with mercury electrodes, and that showed that there was no sensible decrease of thickness with pressure, and that the increase of capacity was not, therefore, due to the effect of mechanical pressure. In reply to Dr. Russell, he said the representation given in the Paper of the condenser with its imperfectly travelling armatures only concerned the alternate current losses. The purely leakage losses could easily be separated out in the manner described. Mr. Addenbrooke had referred to the large temperature coefficient of the conductivity of celluloid, but this had no application to the case of part three, because the voltage applied to the bridge was only of the order of 2 or 3 volts. Mr. Duddell's remarks were very interesting, and showed the considerable influence of brush discharge even at low voltages. In reply to Prof. Lees, tinfoil electrodes under pressure had not been tried in the residual charge experiments, but it was to be expected that under those circumstances we should get a curve intermediate between curves 4 and 5 of Fig. 10. No doubt, as Dr. Eccles suggested, a combination of the two effects described in the first and last parts of the Paper would account for the viscous part of the phenomenon.

XXXV. *On a Method of Measuring the Pressure of Light by Means of Thin Metal Foil.* By GILBERT D. WEST, *B.Sc.*

RECEIVED MAY 29, 1913.

IF a flexible uniform strip of foil suspended vertically be subjected to a small horizontal pressure, the consequent deflection θ is given by

$$\theta = R/\rho,$$

where R is the horizontal force per unit area and ρ is the weight of unit area of the foil. The pressure of bright sunlight is about 5×10^{-8} gramme, and the mass of a square centimetre of gold leaf is about $1 \cdot 6 \times 10^{-4}$ gramme. The end of a strip 10 cm. long should, therefore, be deflected by 0·003 cm., a distance easily observable with a microscope. In the following the above method is developed, and experiments with both gold and aluminium foil are described. The interest of the research lies in the extreme simplicity of the apparatus and in the absence of complicated adjustments. To some extent the experiments resemble those carried out by Prof. Osborne-Reynolds on the impulsion of silk fibres,* but the latter's experiments had for their object an investigation of the gas action.

The Apparatus.

Various methods of mounting the strips of foil were tried, but the method of making a loop at the top was found to be the most satisfactory.

A piece of gold or aluminium foil was bent over upon itself, covered with tissue paper, and the doubled portion then struck at two or three points with a very small round-headed hammer. This was sufficient to make the two pieces of foil adhere and a strip with a loop at the top was thus formed.

A glass tube was then bent into the shape indicated by Fig. 1. AB is a capillary tube, and C is a mercury manometer. It was found an advantage to dust the portion AB with a fine powder, such as red ochre, for otherwise the foil tended to adhere to the glass. The strip was then mounted in a tube (previously dusted with red ochre) as shown in Fig. 1. Three such strips

* Osborne-Reynolds, "Phil. Trans.," Part II., 1879, p. 768.

were prepared for the final measurements, two of aluminium and one of gold. The method of mounting was found to be very satisfactory, and whether the strip was deflected by

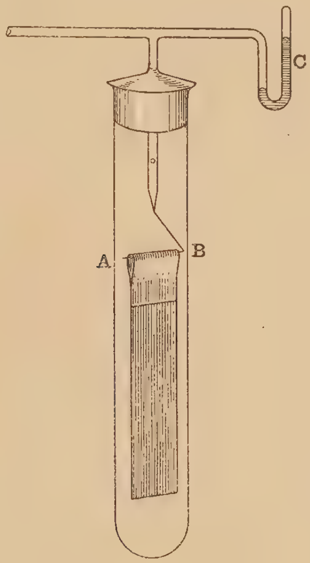


FIG. 1.

rotation of the tube about an axis AB, or by outside electrical attraction the return to the eyepiece zero of the observing microscope was always good.

Source of Radiation.

As a source of radiation a 110-watt carbon filament lamp was used. This lamp, without concentrating lenses but sometimes with a glass screen in front of it, was placed at distances from the strips varying from 12 cm. to 16 cm. It was found necessary to enclose the lamp in an earthed tin box with a hole in the front, as without this deflections could sometimes be obtained by simply charging the filament to 200 volts.

Observing Microscope.

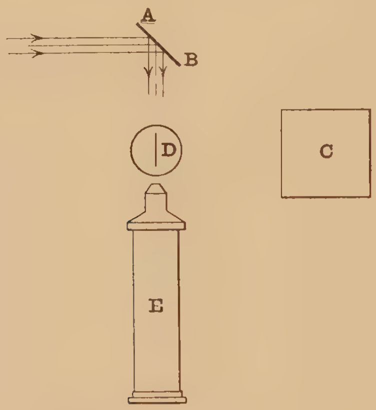
In the observing microscope, use was made of a $\times 20$ eyepiece coupled with an inch objective. By this means, defined mag-

nification of about 200 could be obtained, together with the long working distance essential to the observations.

Weight of the Strips.

The weights of the strips were determined by the bending they produced in a fibre of glass that had been previously calibrated with small pieces of wire of known weight.

Arrangement of Apparatus.



AB is a piece of glass coated with foil reflecting light to illuminate field, C is the source D the strip of foil in tube and E the observing microscope.

FIG. 2.

Miscellaneous Facts.

Calculation shows that the heating of the strip reaches the steady state in a fraction of a second. Inasmuch as the side nearer the source is heated most, there is a small deflection due to the consequent curvature. It can be shown, however, that such a deflection is only about $\frac{1}{1000}$ the deflection produced by the pressure of radiation.

Light incident on a gold or aluminium strip is reflected without much scattering. From experiments carried out with a thermometer, whose bulb was coated with foil, it was found that both gold and aluminium leaf reflected about 84 per cent. of the incident light. The pressure on a square centimetre of foil should thus be equal to 1·84 times the energy per cubic centimetre.

Calculation of the Pressure.

By taking moments about an axis AB we find that R, the radiation pressure, is given by

$$R = \frac{2 \cdot Whd}{Al^2},$$

where W is the weight of the strip (in dynes),

h is the distance of the centre of gravity of the strip below AB,

d is the deflection as measured by the observing microscope,

A is the exposed area of the strip,

and l is its length.

Results Obtained.

Air at Atmospheric Pressure.

The general effect of the incidence of radiation upon the front of a strip is a small motion backwards (sometimes of the order of the deflection required by the pressure of radiation) followed by a more powerful motion forward due to convection currents. Sometimes the motion is a little unsteady at first, but the forward motion due to convection always takes place finally. The magnitude of the convection effect is much reduced by placing a glass screen in front of the lamp, and this reduction is doubtless caused by the decreased heating of the walls of the test tube. No satisfactory observations can be taken with air at atmospheric pressure.

Air at Lower Pressures.

As the pressure is reduced so does the forward convection effect get gradually less, until, at a pressure of a few centimetres of mercury it is not observable. At pressures of about 1 to 2 cm. of mercury, very small convection effects still occur, but the fortunate fact about these effects is that they always act on the same side of the strip and are independent of the side on which the source is placed. Similar results to these were obtained by Hull* in 1905. The effects are probably attributable to the small inclination of the strip to the vertical

* Hull, "Phys. Review," XX., 1905, p. 292.

and to the consequent results of the strip being heated. An example is given below.

Gold strip. Air 1·3—1·6 cm. Hg.		
Distance of source.	Deflections in eyepiece divisions.	
	Source on left.	Source on right.
12 cm.	0·8 towards source	2·9 from source
14 cm.	0·7 towards source	2·1 from source
16 cm.	0·6 towards source	1·6 from source

When the source was on the left the two effects were in opposition, but when the source was on the right they were in conjunction. The true radiation pressure could thus be calculated.

Hydrogen at Atmospheric Pressure.

It is well known that convection effects in hydrogen are much less than in air.* When the tube was filled with hydrogen at atmospheric pressure the convection effects were of the same kind but somewhat smaller than with air at 1 to 2 cm. pressure. An example is given below.

Gold strip. Hydrogen at atmospheric pressure.		
Distance of source.	Deflections in eyepiece divisions.	
	Source on left.	Source on right.
12 cm.	0·7 from source	1·4 from source
14 cm.	0·5 from source	1·2 from source
16 cm.	0·3 from source	1·0 from source

Hydrogen at Low Pressures.

With hydrogen at low pressures the effects obtained were of the same kind as with air at low pressures, but they were somewhat smaller. An example is given below.

Gold strip. Hydrogen 1·3—1·5 cm. Hg.		
Distance of source.	Deflections in eyepiece divisions.	
	Source on left.	Source on right.
12 cm.	0·0 from source	2·0 from source
14 cm.	0·0 from source	1·5 from source
16 cm.	0·0 from source	1·1 from source

* Barlow, "Proc." Royal Soc., A., Vol. LXXXVII., 1912, p. 1.

Measurement of the Energy per Cubic Centimetre.

The measurement of the energy received per square centimetre per second at various distances from the source was made by observing the initial rates of rise of temperature of a blackened copper plate 3 mm. thick enclosed in a test tube. The temperature of the copper plate was indicated by an embedded copper-eureka thermojunction connected to a low resistance D'Arsonval galvanometer. The lampblack was assumed to absorb 95 per cent. of the incident radiation.

	Distance of source.	Energy per Cubic Centimetre.	Pressure of radiation as calculated from the deflections of					
			Gold strip. Width=1·43 cm. Length=6·4 cm. Containing tube=2·4 cm. diameter.			Aluminium strip. Width=1·11 cm. Length=7·64 cm. Containing tube=1·6 cm. diameter.		
			Hydrogen pressure atmospheric.	Hydrogen pressure 1–2 cm. Hg.	Air pressure 1–2 cm. Hg.	Hydrogen pressure atmospheric.	Hydrogen pressure 1–2 cm. Hg.	Air pressure 1–2 cm. Hg.
		Ergs.	Dynes.	Dynes.	Dynes.	Dynes.	Dynes.	Dynes.
s	12 cm.	$3{\cdot}2\times10^{-5}$	$3{\cdot}3\times10^{-5}$	$3{\cdot}5\times10^{-5}$	$4{\cdot}0\times10^{-5}$	$3{\cdot}7\times10^{-5}$	$2{\cdot}5\times10^{-5}$	$3{\cdot}5\times10^{-5}$
	14 cm.	2·5	2·7	2·6	2·9	3·0	2·3	3·2
	16 cm.	1·9	1·8	2·0	2·4	2·6	2·0	2·3
s	12 cm.	2·5	2·9	2·5	2·7	2·6	2·9	2·9
	14 cm.	1·8	2·2	1·9	1·8	2·1	2·1	1·8
	16 cm.	1·4	1·7	1·4	1·3	1·5	1·5	1·3

An exactly similar set of results was obtained with an aluminium strip 1·66 cm. wide, 7·3 cm. long and enclosed in a tube 2·4 cm. diameter. The fact that the majority of results are rather high suggests the existence of either a radiometer effect or some constant error in one of the measuring instruments.

The measurement of the radiation pressure by the means described is so simple that there is now no reason why it should not be included in a course of laboratory experiments.

In conclusion, I desire to thank Prof. Lees for his encouragement and suggestions and for the facilities placed at my disposal at East London College.

ABSTRACT.

The pressure of the radiation emitted by a carbon filament lamp at a distance of a few centimetres is sufficient to cause a microscopically measurable deflection of the end of a suspended strip of gold or aluminium foil, and by this means the radiation pressure can

be calculated knowing the weight of the strip. The results agree to within about 10 per cent. with the energy content per cubic centimetre as measured by the initial rate of rise of temperature of a copper plate exposed to the radiation.

The best results are obtained by working in an atmosphere of hydrogen, 1 cm. to 2 cm. pressure, but good results are obtained with hydrogen at atmospheric pressure. Air at 1 cm. to 2 cm. pressure also gives good results.

The method involves no laborious adjustments, and the apparatus is not seriously affected by vibration.

DISCUSSION.

Prof. C. H. Lees remarked that the point in the above Paper was its extreme simplicity.

Dr. G. Barlow (in some remarks communicated by Prof. Poynting) pointed out that the author ought to allow for the light reflected from the foil to the glass wall and back again to the foil. This would improve the agreement in the author's measurements.

XXXVI. *The Quantum Theory of Energy and the Emission of Electricity from Hot Bodies.*

By WILLIAM WILSON, *Ph.D., Wheatstone Laboratory, King's College, London.*

RECEIVED JUNE 9, 1913.

THE quantum theory was introduced by Planck* in order to arrive at a formula representing the distribution of energy in the spectrum of the radiation from a black body. For the purposes of the present Paper Planck's formula may be put in the form

$$I_\nu d\nu = C\nu^3 \frac{d\nu}{e^{\frac{h\nu}{kT}} - 1}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $I_\nu d\nu$ represents the quantity of energy within the frequency limits ν and $\nu + d\nu$ emitted per second by the "resonators" of the radiating material, T is the absolute temperature, C is a suitable constant and h and k are universal constants of nature. Comparison of the results of measurement on the radiation of a black body with this formula and with the Boltzmann-Stefan formula for the total radiation from a black body give for these constants the values

$$h = 6{\cdot}415 \,.\, 10^{-27} \text{ erg-seconds},$$

$$k = 1{\cdot}34 \,.\, 10^{-16} \text{ ergs per degree}.$$

The latter constant is identical with the absolute gas constant reckoned for one molecule. It is possible, therefore, to deduce from measurements on black radiation the number of molecules of an ideal gas per cubic centimetre under standard conditions of pressure and temperature. Planck finds this number to be

$$2{\cdot}77 \,.\, 10^{19}.$$

A further consequence is the deduction of the elementary charge of electricity. This can be deduced from this last number, and the results of electrolysis, and is found to be

$$e = 4{\cdot}67 \,.\, 10^{-10} \text{ electrostatic units}.$$

In deducing his formula, Planck assumes that the radiating

* "Ann. d. Physik," Bd. 4, p. 553 (1901); Bd. 4, p. 564 (1901); "Theorie der Wärmestrahlung." Second edition.

body contains a number of "resonators" which emit their energy in a discontinuous way. Let us suppose, for example, that one of these "resonators" at a certain instant has no energy. It will, on Planck's hypothesis, absorb energy continuously from the surrounding radiation. When its energy reaches the value $h\nu$, where ν is the frequency of the "resonator" and h the constant already mentioned, it *may* emit the whole of its energy. If emission does not occur, it will continue to absorb energy till the amount $2h\nu$ has been acquired, when the emission of the whole of its energy may occur, and so on. Emission *only* occurs when the energy of the "resonator" is an integral multiple of $h\nu$, the actual occurrence of the emission being a matter of chance.

Not only does Planck's formula represent accurately the distribution of energy in the black spectrum, but the hypothesis of discontinuous emission which was used by Planck to deduce the formula seems to admit of a very wide application. Hughes,* for example, concludes that the energy of electrons emitted from metals illuminated with ultra-violet light is equal to a constant multiplied by the frequency of the light, and this constant is very nearly equal to Planck's h. Prof. O. W. Richardson and Mr. Compton† have also arrived at similar conclusions. Further, the value recently obtained by Prof. Barkla and Mr. G. H. Martyn‡ for the wave-length of the Röntgen radiation used in their experiments closely accords with the value obtained from the equation

$$\tfrac{1}{2}mv^2=h\nu, \qquad \qquad (2)$$

when we substitute for m and v the mass and velocity respectively of the electrons which would be emitted if the radiation were absorbed by a metal, and for h the value given by Planck.

The above considerations justify an attempt to apply Planck's theory to the phenomena of emission of electrons from hot bodies, and they suggest that emissions of energy take the form of ejection of electrons. Prof. Nicholson§ has also adopted this hypothesis in his work on the constitution of the solar corona.

* Hughes, "Phil. Trans.," Vol. CCXII. (A), p. 205 (1912), and "Phil. Mag.," Vol. XXV., p. 683 (1913).

† Richardson and Compton, "Phil. Mag.," p. 576 (1912).

‡ Barkla and Martyn, "Proc. Phys. Soc. of London," Vol. XXV., p. 214 (1913).

§ "The Constitution of the Solar Corona II.," Monthly Notices of R.A.S., June, 1912.

Let us suppose we have a hot body—*e.g.*, platinum—in a field of black radiation. The emission of the energy

$$I_\nu d\nu = C\nu^3 \frac{d\nu}{e^{\frac{h\nu}{kT}} - 1}$$

is accomplished by the ejection of dN electrons. Each electron at the moment of emission from the resonator or atom has a quantity of energy equal to an integral multiple of $h\nu$, so that we may write

$$C\nu^3 \frac{d\nu}{e^{\frac{h\nu}{kT}} - 1} = \bar{n} h\nu dN, \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $\bar{n}$ is the average value of the integer in question. If we put $\varepsilon = h\nu$, and suitably modify the constant C, the last equation will take the form

$$C\varepsilon^2 \frac{d\varepsilon}{e^{\frac{\varepsilon}{kT}} - 1} = \bar{n} dN. \quad . \quad . \quad . \quad . \quad . \quad . \quad (3\text{A})$$

Most of these dN electrons probably never leave the molecule within which they are emitted at all, but simply leave one atom and attach themselves to another. In doing so they contribute $I_\nu d\nu$ to the radiant energy within the frequency limits ν and $\nu + d\nu$.

The following considerations will assist us in dealing with the number $\bar{n}$. If the probability of an emission within the frequency range ν to $\nu + d\nu$ is very great, $\bar{n}$ will approach unity. On the other hand, if this probability is very small $\bar{n}$ may be very great. The simplest hypothesis we can introduce to connect $\bar{n}$ and the probability η of an emission is that expressed by the equation

$$\bar{n} = \frac{1}{\eta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Planck finds for η the value

$$\eta = \frac{e^{\frac{\varepsilon}{kT}} - 1}{e^{\frac{\varepsilon}{kT}}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

From (3*a*), (4) and (5) we get the very simple equation

$$C\varepsilon^2 e^{-\frac{\varepsilon}{kT}} d\varepsilon = dN. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The number of electrons emitted by the "resonators" whose energy exceeds a certain value w will be given by

$$N = C\int_w^\infty \varepsilon^2 e^{-\frac{\varepsilon}{kT}} d\varepsilon. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

It is likely that only electrons from the surface layer of molecules leave the metal, and, if w is the smallest amount of energy an electron can have in order to leave a molecule in the surface layer, equation (7) will, if a suitable value is given to C, represent the quantity of electricity emitted per second from a square centimetre of the surface of the metal. On integrating (7) we get the formula

$$Q=KT\left(1+2\frac{k}{w}T+2\frac{k^2}{w^2}T^2\right)e^{-\frac{w}{kT}}, \quad . \quad . \quad . \quad . \quad (8)$$

where K is a suitably chosen constant.

The following table gives the leak observed by H. A. Wilson* from a platinum wire which had been treated with nitric acid, and also the leak as calculated from O. W. Richardson's formula

$$Q=aT^{\frac{1}{2}}e^{-\frac{w}{kT}},$$

$$a=6\cdot9\,.\,10^7,$$

$$\frac{w}{k}=6\cdot55\,.\,10^4.$$

In the third column is given the leak as calculated from formula (8). The constants w and K were calculated by making the formula agree with the extreme values 15·7 at 1,375°C. and 1,280 at 1,580°C. For w/k the value 6·376 . 10⁴ was used. The term $2\frac{k^2}{w^2}T^2$ was neglected in the calculation, since it would only affect the result by less than $\frac{1}{4}$ per cent. if the temperature were 2,000° abs., and, of course, to a smaller extent at lower temperatures.

Temperature in degrees Centigrade.	Leak observed per square centimetre.	Leak calculated by formula (8).	Leak calculated by Richardson's formula.
1,375	15·7	15·7	14·9
1,408·5	34·3	34·6	33·3
1,442	74·6	74·1	71·8
1,476	152	155·7	153
1,510·5	323	321·8	318
1,545	638	647	645
1,580	1,280	1,280	1,285

* H. A. Wilson, "Phil. Trans.," Vol. CCII. (A), p. 258 (1904). J. J. Thomson, "Conduction of Electricity through Gases," p. 202, second edition. The unit of current used in the table is 10^{-9} amperes.

It will be seen that formula (8) is in distinctly better accordance with the experimental values than is Richardson's formula.

The foregoing may be briefly summarised in the following way. A definite theory has been proposed for the phenomena of emission of electricity from hot bodies. This theory is based on certain hypotheses as to the manner in which interchange of energy between a radiating body and the surrounding radiation occurs. The assumption that energy is emitted by the ejection of electrons each carrying an integral multiple of $h\nu$ units of energy has led to a formula which represents the facts better than that hitherto used, while it has the important advantage of being applicable to a wide range of phenomena. It has been used with great success in accounting for the origin of the coronal spectral lines and is in accordance with the latest experimental results on photo-electric phenomena and Röntgen rays.

3RD JUNE, 1913.

ABSTRACT.

The Paper gives a theory of the emission of electricity from hot bodies which is based on the quantum theory of energy. A formula connecting the thermionic current and the temperature of the emitting body is deduced. This formula closely resembles that of Richardson, and agrees slightly better with experimental results.

DISCUSSION.

Prof. J. W. NICHOLSON thought the Paper was a valuable one in that it connected up yet another phenomenon with Planck's quantum theory of radiation. It was probable that Planck's constant h was in some way an electron constant, and that the emission of energy was discontinuous because emission of electrons was discontinuous.

XXXVII. *Note on the Resistivities of Glass and Fused Silica at High Temperatures.* *By* ALBERT CAMPBELL, *B.A.* (*From the National Physical Laboratory.*)

RECEIVED JUNE 18, 1913.

SOME years ago (1906) we made some tests of the insulation resistance of fused quartz, glass and mica at various temperatures. As the resistivities of such materials have not yet been thoroughly investigated, I give below (by the kind permission of the Thermal Syndicate) some of the results obtained in our experiments. They must be taken as giving the order of magnitude of the resistivities rather than highly accurate numbers, for the walls of some of the tubes were somewhat irregular, and no great elaboration of apparatus or methods was employed. In the case of the silica and glass the tests were made on tubes about 30 cm. long, 1 cm. to 4 cm. diameter, and of wall thicknesses between 0·05 mm. and 0·12 mm.

The mean thicknesses were obtained from the density and the mass, due estimates being made of the effect of want of uniformity.

The tubes were platinized inside and outside for a considerable part of their length. Towards each end beyond the platinized surfaces there were bare strips, and beyond these were platinized bands, to which guard wires were connected. All the connections to the platinized surfaces were made by means of nickel wires.

Most of the glass tubes were entirely closed at one end, so as to require only one guard strip. The guard wires were arranged in the well-known manner to avoid all surface leakage. For the high temperatures the tubes were heated in a suitable electric furnace, and the temperature was measured by a calibrated thermocouple.

The resistance measurements were made by the direct deflection method, using a galvanometer with a set of shunts. The readings were taken after a time of electrification of one minute, and the voltage employed was either 200 or 500 volts, except for a few of the readings at the highest temperatures, which were taken with 2 volts.

The mica was tested in the form of a thin sheet, with platinized areas on each face and a rim for the guard wire.

In the following table are given the results, which have in some cases been averaged from several experiments. It will be noticed that at 750 deg. the Jena combustion glass conducted fairly well. With 2 volts the apparent resistance of the piece tested rose quickly from 150 to 600 ohms owing to polarization.

Material.	Description.	Temperature, deg, C.	Resistivity, megohm-cm.
Fused silica ...	Silky surface.........	15	Over 200,000,000
		150	Over 200,000,000
		230	20,000,000
		250	2,500,000
		300	200,000
		350	30,000
		450	800
		700	30
		800	About 20
		850	About 20
Glass	Ordinary (soda-lime)	18	500,000
		145	100
Glass	"Geräte" (zinc-aluminium)......	18	3,000,000
Glass	Jena (combustion tubing)	18	Over 200,000,000
		115	36,000,000
		150	18,000,000
		750	0·01 to 0·04
Mica	0·026 mm. thick ...	18	Over 300,000,000
		135	Over 300,000,000

It is clear from the above somewhat meagre figures that the subject would repay much fuller investigation. In the case of mica the resistivity is reduced very considerably at the higher temperatures, but still not nearly as much as for the other materials mentioned above.

JUNE 5, 1913.

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